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MEMORANDUM

Subject: Progress Report 008
Chaotic LIDAR for Naval Applications: FY12 Progress Report (7/1/2012– 9/30/2012)

This document provides a progress report on the project "Chaotic LIDAR for Naval Applications" covering the period of 7/1/2012– 9/30/2012.

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Award Information

Award Number	N000141010906
Title of Research	Chaotic LIDAR for Naval Applications
Principal Investigator	William D. Jemison
Organization	Clarkson University

Technical Section

Technical Objectives

The original proposal identified the following three tasks:

- Task 1 involves the generation and characterization of a wideband chaotic lidar (CLIDAR) signal suitable for system-level experiments.
- Task 2 involves a system-level investigation into the underwater propagation/scattering characteristics of the CLIDAR signals. The investigation will be performed as a function of both optical wavelength and water turbidity (absorption and scattering) in order to determine the range resolution/accuracy and signal to noise performance that can be expected using CLIDAR.
- Task 3 involves the development of an advanced chaotic laser, or CLASER, for use as a compact and cost-effective optical source for CLIDAR. This approach integrates a laser gain medium into an OOR to produce an integrated chaotic optical source.

Progress Statement Summary

Early in the program Task 1 efforts focused on the feasibility of using the open optical resonator (OOR) approach to produce wideband chaotic laser signals. This task was identified as a precursor to Task 3. Last year we reported that we abandoned the OOR approach in favor of a fiber ring laser approach for several reasons. This effectively allowed us to focus more effort on the more important Task 3. We also reported the development of two infrared (IR) low-power fiber ring lasers that exhibited wide instantaneous bandwidth.

Significant progress has been made this past year towards the development of a fiber laser that will satisfy three critical requirements which are 1) an output wavelength in the blue-green; 2) sufficient output power to support underwater experiments; and 3) a chaotic output with an instantaneous bandwidth of at least one gigahertz. To achieve this we adopted a laser design that consisted of low-power chaotic laser source (to achieve the bandwidth), a two-stage fiber amplifier (to achieve high power), and a frequency doubler (to convert from the IR wavelength of 1064nm to a blue-green wavelength of 532nm).

Specifically, we adopted a fiber Fabry-Perot architecture in favor of the fiber ring architecture to reduce cavity losses, which resulted in improved performance with a 20x increase in optical power output from the chaotic laser. This greatly improved our ability to amplify the chaotic laser output. Numerical modeling software was developed based on fundamental laser physics to predict fiber amplifier performance. The pre-amplifier was developed and produced output powers that approached those predicted by simulation. The gain amplifier has also been developed and is producing an output power at 1064 nm of over 5W. The frequency doubler uses a non-linear PPKTP crystal with associated input and output lenses to preserve optical beam quality. The doubler was tested using a commercially available 700mW 1064 nm source and efficiencies were achieved that exceeded the manufacturer's data sheet

specification. The doubler is now being integrated with the chaotic laser, preamplifier, and gain amplifier. Once this integration is accomplished, the CLIDAR transmitter will be complete and system-level investigations planned in Task 2 can start.

Progress

The majority of the effort last year was focused on Task 3, the development of a chaotic laser. For the Navy application such a laser must satisfy three critical requirements which are 1) an output wavelength in the blue-green; 2) sufficient output power to support underwater experiments; and 3) a chaotic output with instantaneous wideband of at least one gigahertz. To achieve this we adopted a laser design that consisted of low-power chaotic laser source (to achieve the bandwidth), a two-stage fiber amplifier (to achieve high power) consisting of a fiber pre-amplifier and a fiber gain amplifier, and frequency doubler (to convert from the IR wavelength of 1064nm to a blue-green wavelength of 532nm). Progress on each of these areas (listed below) will be described.

1. Chaotic Laser Signal
2. Preamplifier Simulation and Results
3. Gain Amplifier Simulation and Results
4. Frequency Doubler Experimental Results

<u>Chaotic Laser Signal</u>

Our approach for generating the desired instantaneous bandwidth is to use long-cavity fiber lasers. A long cavity will support the simultaneous lasing of thousands of longitudinal laser modes over the laser gain bandwidth which produces the desired instantaneous frequency bandwidth. Last year we

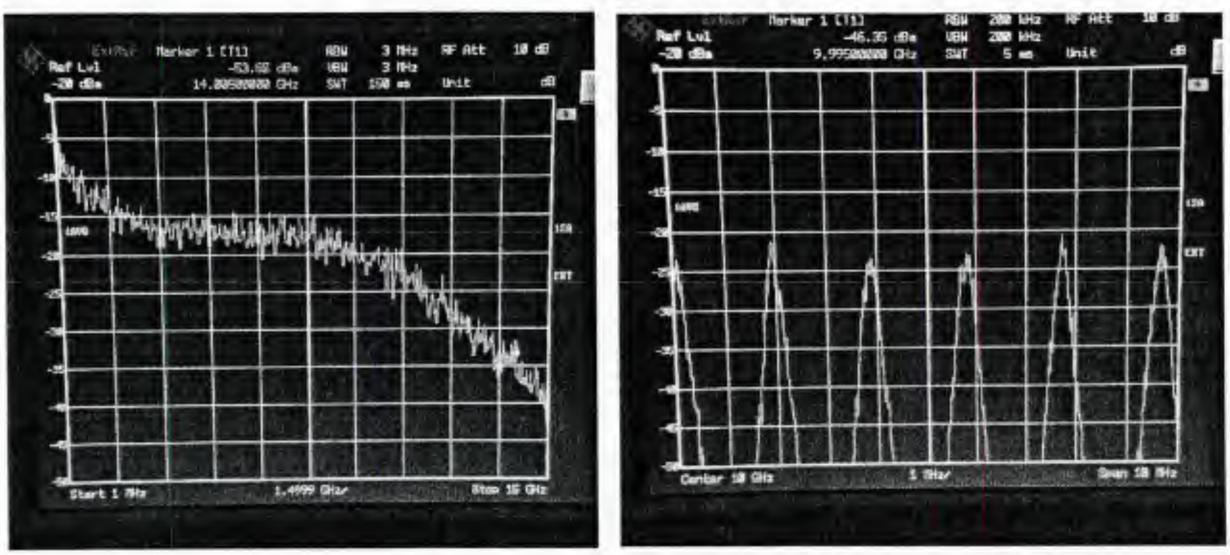


Fig 1. Chaotic wideband signal source. Left: Full spectrum of laser modulation frequencies, showing content from 0 to 15 GHz. Right: Close up of longitudinal modes; thousands of these modes constitute the full 15 GHz spectrum.

demonstrated chaotic lasers at 1550 nm and 1064 nm. Their rich frequency content from DC to 15 GHz makes them excellent potential sources for high resolution imaging and ranging. The 1550 nm laser was developed as an initial proof-of-concept since components are readily available at this commercial telecommunications wavelength. Once this was demonstrated we moved to 1064nm, a wavelength that could be doubled to the blue-green wavelength of 532nm. However, the fiber ring configuration introduced significant cavity losses that limited the output power of these lasers. For example, the output of the chaotic fiber ring laser is about 3mW when pumped with 280mW of 974nm light. This proved to

be insufficient for subsequent amplification, as the preamplifier became ASE-limited at 25mW. A redesigned chaotic fiber laser using a Fabry-Perot cavity configuration emitted over 60mW, a x20 increase over the fiber ring configuration, allowing for full amplification. The Fabry-Perot laser configuration and experimental output power is shown in the following figure.

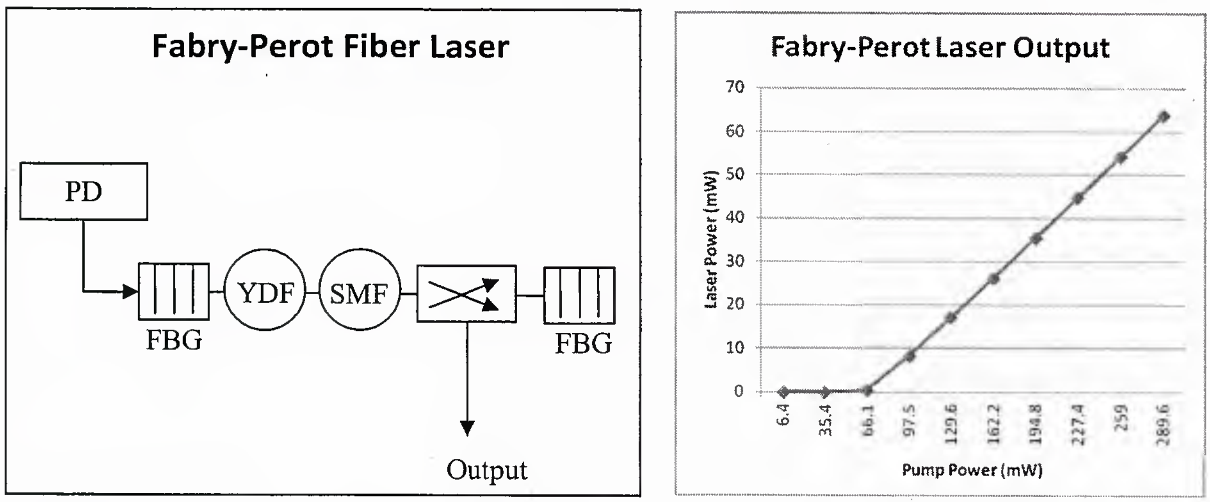


Fig 2. Fabry-Perot chaotic fiber laser. Left: Block diagram of the laser. Right: Output power versus pump power. (PD: Pump Diode; FBG: Fiber Braggs Grating; YDF: Ytterbium Doped Fiber; SMF: Single Mode Fiber.)

Preamplifier Simulation and Experimental Results

The preamplifier was designed to take a nominal 20mW signal and amplify it to 200mW, a gain of 10dB. Numerical simulations of the fundamental laser rate equations predicted that this amplification could occur in 30cm of ytterbium doped fiber, in a single-pass forward-pumped configuration. Figure 3 shows the predicted inversion ratio, gain, and output power of the fiber preamplifer.

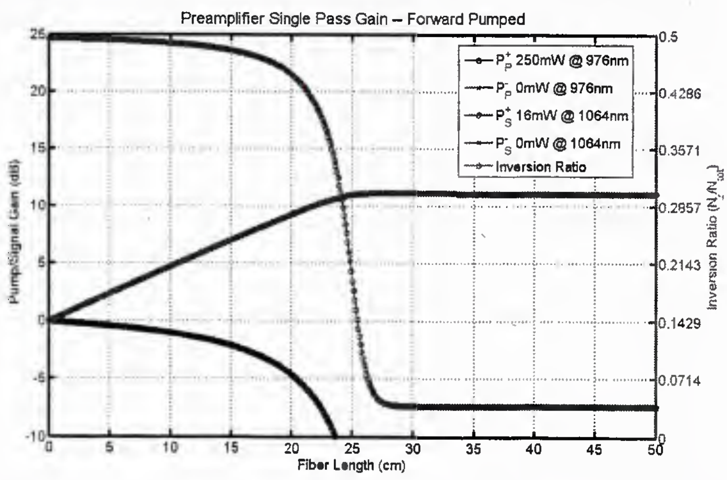
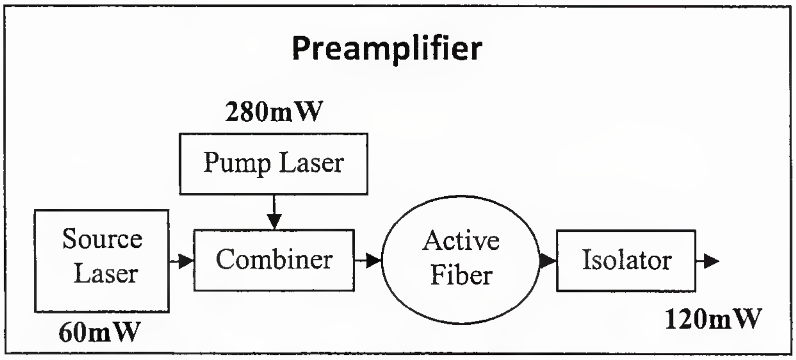


Figure 3. Simulated preamplifier performance. Using a 280mW diode laser to core-pump Yb-doped fiber in a forward pumped, single-pass configuration results in an output signal of 200mW.

The experimental preamplifier performance lagged the simulation predictions. The initial attempt at amplifying using the fiber ring laser failed at an output level of just 25mW, when the preamplifier started

amplifying ASE noise rather than the laser signal. After revising the chaotic laser configuration to a Fabry-Perot, the preamplifier amplified the signal only, up to a level of 175mW. This represents a pump-to-signal conversion efficiency of about 40%, significantly below the specified conversion efficiency of 78%. The cause of this discrepancy is still under investigation, but may lie in a non-optimal doped fiber length or a pump wavelength that is off the ytterbium absorption peak. The preamplifier did, however, produce enough power to allow the second stage gain amplifier to perform effectively. The preamplifier system block diagram and photograph is shown in the following figure.



Seed and Preamplifier:

1. Pump diode
2. Seed laser including 100 m SMF
3. Preamplifier including output isolator
4. Metering for output power

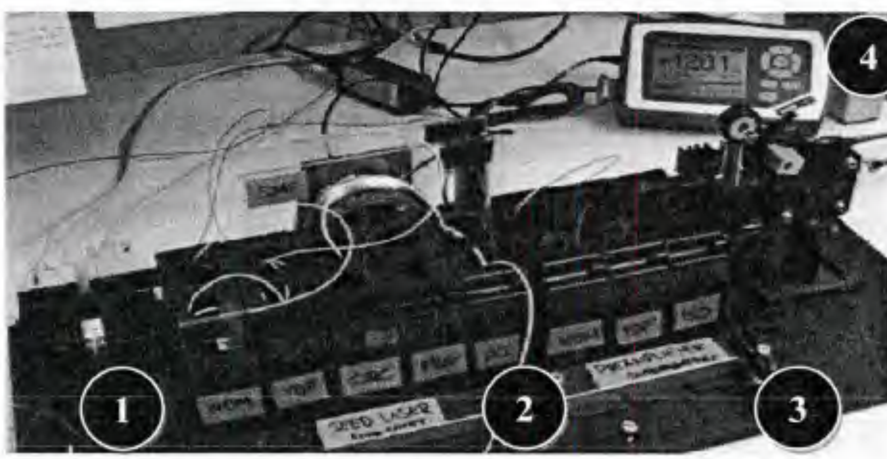


Figure 4. Actual preamplifier performance. Top: Preamplifier block diagram. Bottom: Using a 280mW diode laser to core-pump Yb-doped fiber in a forward pumped, single-pass configuration results in an output signal of 175mW (120mW after the isolator).

Gain Amplifier Simulation and Experimental Results

The gain amplifier was designed to take a 200mW signal and amplify it to 10W, a gain of 17dB. Numerical simulations of the fundamental laser rate equations predicted that this amplification could occur in 3-4m of ytterbium doped fiber, in a single-pass forward pumped configuration. Multiple fiber-coupled high power pumps are necessary to deliver the required 20W of pump power. The following figure shows the predicted output power of the fiber amplifier.

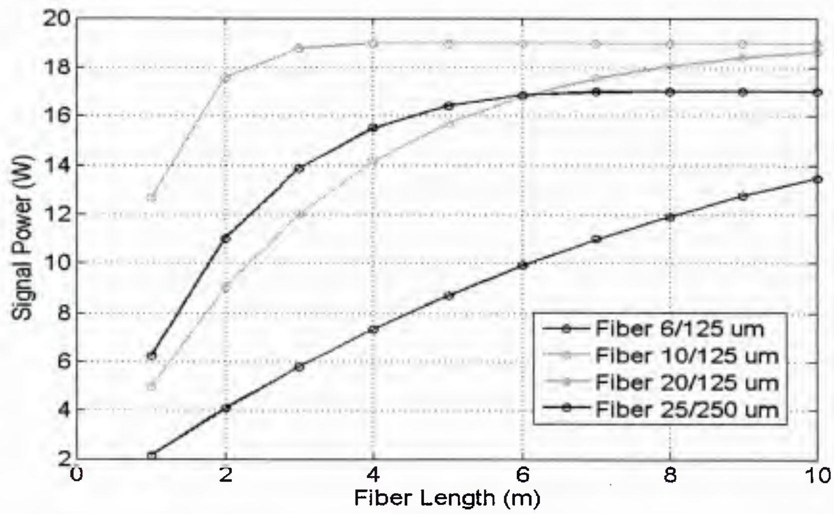
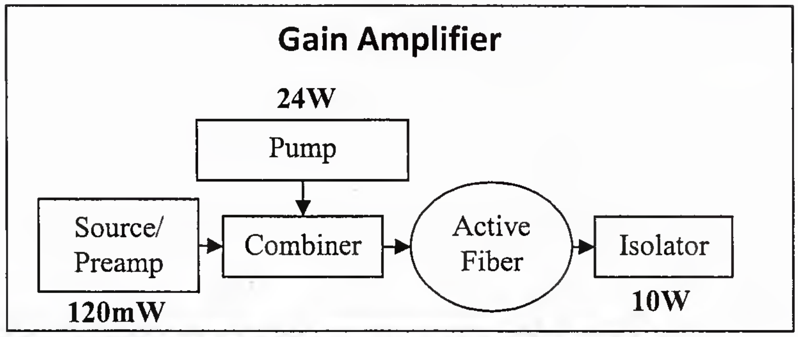


Figure 5. Simulated gain amplifier performance. Several fiber types are shown; for performance and compatibility the 10/125DC was chosen. Following the 10/125DC green line, by using 20W of pump power to cladding-pump double-clad Yb-doped fiber in a forward pumped, single-pass configuration, an output signal of 12W after 3m of fiber, and 14W after 4m, is predicted.

While the experimental gain amplifier performance was satisfactory, it did vary from the simulated predictions. The maximum pump power that has been delivered to the fiber is estimated to be 10W, which resulted in a signal output of 5.1W. This represents a conversion efficiency of 50%, vs. the expected 75%. Investigation is ongoing into the cause of this discrepancy, and fiber length changes may have to be made in the future. Even projecting this efficiency to the full pump strength of 20W, however, the amplifier should be able to deliver the desired 10W in the IR for doubling to green. This will be confirmed in upcoming tests.

The polarization and signal behavior were tested at the output of the amplifier stages. Both were found to be largely unchanged from the original chaotic source laser, so this IR signal is appropriate for use in producing a CLIDAR signal in green light. A block diagram and photograph of the gain amplifier is shown below.



Gain Amplifier:

1. Power supplies
2. Pump diodes and cooling
3. Fiber pump/signal combiner
4. Active ytterbium doped fiber
5. Metering for temperature, back reflection, and output power

Figure 6. Actual gain amplifier performance. Top: Gain amplifier block diagram. Bottom: Using three fiber-coupled diode lasers to cladding-pump Yb-doped double-clad fiber in a forward pumped, single-pass configuration results in an output signal of 5.15W. Each pump laser is running at 4W, so this represents an in-fiber conversion efficiency of about 50%.

Frequency Doubling Experimental Results

Wavelength conversion has been performed using a temperature controlled, periodically poled crystal for frequency doubling. A test assembly was constructed using a commercial 700mW 1064nm laser, whose beam was expanded to 15mm and then focused through the long, narrow (0.5 x 0.5 x 20 mm) PPKTP crystal. Conversion efficiencies of 1.5% per W were reached while maintaining beam quality and collimation. This efficiency exceeded the manufacturer's specification and we expect to exceed 1 W of green light when a 10 W IR signal is used.

Having demonstrated that this optical assembly can be used for successful frequency, the assembly is now being integrated with the laser and amplifier stages to produce the chaotic signal in green light.

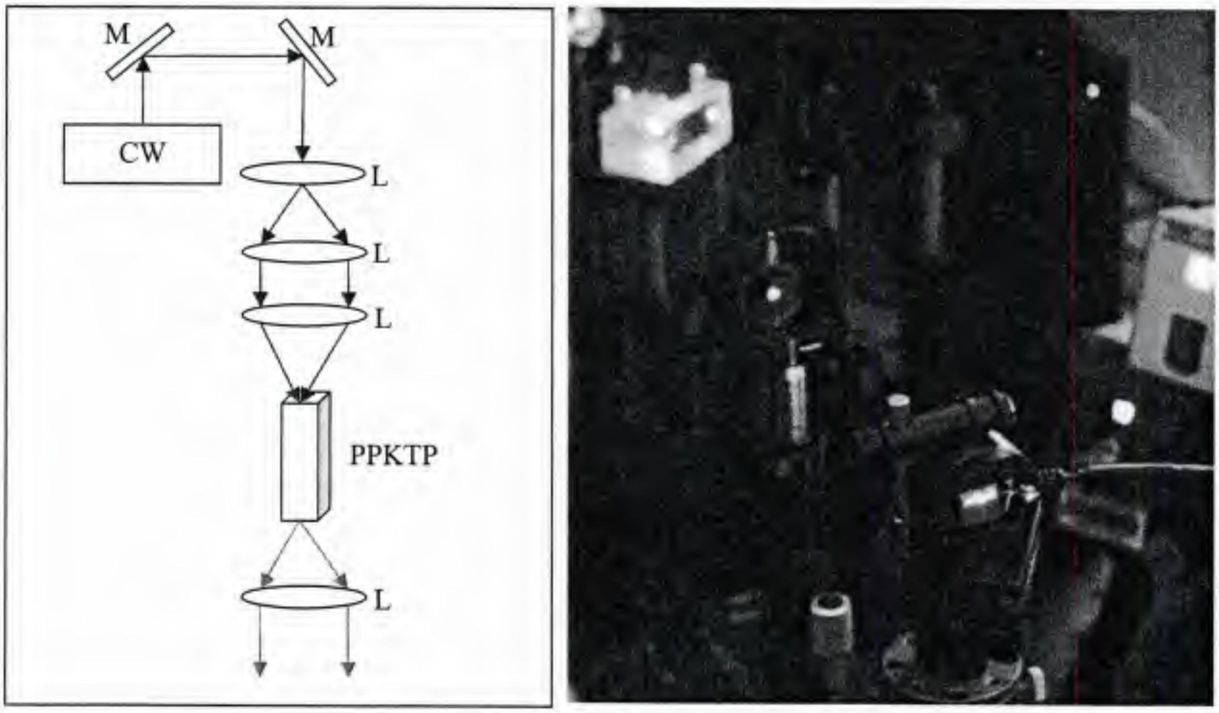


Fig 3. Frequency doubling from IR to green. Left: Block diagram of frequency doubling scheme, showing beam expanding and then focusing on the crystal, which changes the IR (red) to green light. Right: Photo of doubling setup; infrared light enters and visible green light exits the crystal. (L: Lens; M: Mirror; CW: Continuous wave source; PPKTP: periodically poled KTP crystal.)

Conclusion

The chaotic laser sources developed are low power infrared (IR) sources, so amplification and wavelength conversion were both necessary before system testing could be performed to prove the effectiveness of this source. A high power frequency doubling circuit has been implemented to deliver a high power, wide bandwidth green signal, which will be suitable for underwater LIDAR. This circuit is intended for use with the 1064 nm laser, to generate 500 mW of optical power at 532 nm, with greater than 1 GHz of instantaneous signal bandwidth. Two amplifier stages have been used to bring a 60mW IR signal up to 5W IR; this power level allows delivery of ~100 mW green light nonlinear conversion. Continuing development will allow amplification to 10 W IR and beyond, for the desired 0.5-1 W green light.

After integration of this source, preamplifier, gain amplifier, and frequency doubler is complete, system tests will be performed as outlined in Task 2.

Chaotic LIDAR for Naval Applications
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Objective:

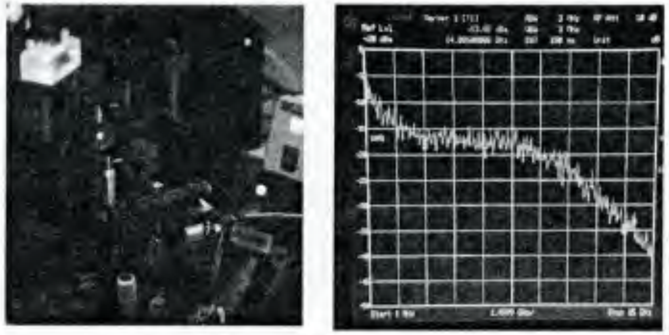
Investigate chaotic LIDAR for high resolution imaging and ranging.

- Develop a chaotic laser for use as a compact and cost-effective wideband optical source
- Perform system-level investigations into the underwater propagation/scattering characteristics chaotic laser signal in order to determine the range resolution/accuracy and signal to noise performance that can be expected from this approach

Approach:

- Use long-cavity fiber lasers to support simultaneous lasing modes
- Use a two-stage fiber amplifier to achieve sufficient optical power for doubling.
- Use a PPKTP crystal for frequency doubling to the blue-green

Figure:



The frequency content of the chaotic fiber laser developed for underwater LIDAR is comprised of many simultaneous lasing modes which generate a wide instantaneous bandwidth.

Scientific or Naval Impact/ Results:

- Introduced a long-cavity fiber laser as novel means of generating wideband signals.
- Demonstrated potential for underwater application of the laser signal through amplification and wavelength conversion to the blue-green.
- Investigating a custom signal processing solution to leverage wide bandwidth for LIDAR.
- Will characterize the underwater optical channel over a wide bandwidth to determine optimum frequency modulation for backscatter reduction.